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A Damage Level Assessment Model for Extra High Voltage Transmission Towers

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***Abstract*—**Power failure resulting from tower collapse due to violent seismic events might bring enormous and inestimable losses. The Chi-Chi earthquake, for example, strongly struck Taiwan and caused huge damage to the power system on September 21, 1999. Nearly 10% of extra high voltage (EHV) transmission towers were damaged in the earthquake. Therefore, seismic hazards of EHV transmission towers should be monitored and evaluated. The ultimate goal of this study is to establish a damage level assessment model for EHV transmission towers. The data of earthquakes provided by Taiwan Central Weather Bureau serve as a reference and then lay the foundation for earthquake simulations and analyses afterward. Some parameters related to the damage level of each point of an EHV tower are simulated and analyzed by the data from monitoring stations once an earthquake occurs. Through the Fourier transform, the seismic wave is then analyzed and transformed into different wave frequencies, and the data would be shown through a response spectrum. With this method, the seismic frequency which damages EHV towers the most is clearly identified. An estimation model is built to determine the damage level caused by a future seismic event. Finally, instead of relying on visual observation done by inspectors, the proposed model can provide a power company with the damage information of a transmission tower. Using the model, manpower required by visual observation can be reduced, and the accuracy of the damage level estimation can be substantially improved. Such a model is greatly useful for health and construction monitoring because of the advantages of long-term evaluation of structural characteristics and long-term damage detection.

***Keywords*—**Smart grid, EHV transmission tower, response spectrum, damage level monitoring.

I. Introduction

THE high demand of household and industrial power is now met by the use of three north-south backbone EHV transmission lines in Taiwan. Therefore, the safety of the 345 kV EHV transmission system is extremely important. Located in the Ring of Fire, about 23,000 earthquakes occur in Taiwan every year, and they probably bring huge economic losses. The Chi-Chi earthquake, a devastating earthquake, for example, strongly struck Taiwan on September 21, 1999, killing about 2000 people and causing NT$360 billion economic losses. In addition, the Chi-Chi earthquake resulted in the second power failure in that year. A large number of power plants, substations, electric towers and transmission lines in the central Taiwan were damaged, leading to large-scale power failure in northern Taiwan, causing the loss of NT$63.7 billion [1], [2].

The Chi-Chi earthquake damaged 307 of 3,714 345 kV EHV towers in Taiwan, and the event shows that the tower damage may lead not only to power outages but to a larger regional chain hazards [3]. Static load, ice damage analysis, wind and impact load are often used in analyses of EHV towers. However, few studies show the relation between the seismic force and EHV towers [4]-[6]. In view of earthquakes frequently occurring in Taiwan, a reliable assessment model of damage state for EHV transmission towers is highly needed.

Although the question regarding the relation between the seismic force and EHV towers remains unanswered, many studies have discussed how earthquakes affect buildings and bridges. One of the studies assessed the damage state of a building after the earthquake by analyzing the acceleration and drift ratio of specific points in the building with 30 accelerometers. By applying double integral and fast Fourier transform (FFT) to the raw data of the acceleration, a cross spectrum and a response spectrum were mapped to estimate the damage state of each point in the building [7]. Another study examined a primary school in Rotonda, Italy, after an earthquake occurred. The damage state of a building could be determined by using the temporary or permanent period elongation [8]. In addition, the fragility curves might be the key to assess the damage from an earthquake, and therefore the probability of the damage level could be gauged by measuring the peak ground acceleration (PGA) [9], [10].

The importance of seismic hazards for EHV transmission towers should never be underestimated. In particular, for countries located in earthquake-prone areas such as Japan, Philippines and Taiwan, earthquakes are undoubtedly one of the most severe threats to EHV transmission towers. So far, electricity companies could only deploy inspectors to examine the damage state of EHV towers, which requires a large amount of manpower and money. Research on the impacts of earthquakes on EHV towers is definitely imperative. Thus, the main purpose of this study is to establish a reliable assessment model for analyzing properties of EHV transmission towers. Two of the most important keys to construct a damage level assessment model for EHV transmission towers are modal establishment of EHV towers and modal analysis. The study uses SAP2000 as the software for the finite element analysis, and A4 EHV transmission tower is the research target for modal establishment. The response spectrum of a specific point on the EHV tower model is mapped after the analysis and simulation.

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The flowchart of the whole procedure mentioned above is shown in Fig. 1.

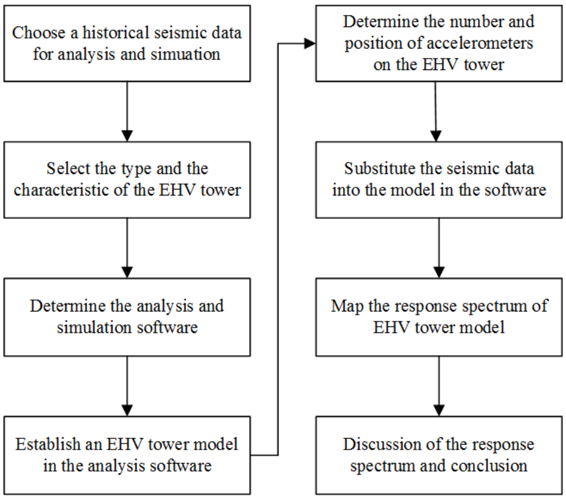


Fig. 1 The flowchart of analyzing the responses of the EHV transmission towers

Once the assessment model is established, the raw data of the Chi-Chi earthquake and its actual damage level are applied to the model to verify the reliability and feasibility of the model. Based on the results of this study, the damage state of EHV transmission towers can be provided to electricity companies to save a great deal of resources, ensure the accuracy of the damage level assessment of EHV transmission towers and set up the maintenance priorities for EHV transmission towers after earthquakes strike.

II. Modal Establishment of EHV Transmission Towers

One of the key elements in simulating the response of an EHV transmission tower hit by seismic waves is the modal establishment of EHV transmission towers. To construct a model of the EHV transmission tower, the simulation software is undoubtedly the most essential element. There are a few choices among seismic analysis software programs, such as ETABS, SAP2000, Midas Gen, Midas Civil and PERFORM 3D. Considering the needs of the arithmetic speed, difficulty in building an EHV tower model and embedding the specification of a national structural design, SAP2000 might be the best choice for EHV transmission tower modal establishment and modal analysis. SAP2000 is finite element analysis software introduced by Computers and Structures, Inc., which is widely used in the seismic analysis and structural response in seismology and civil engineering. SAP2000 performs well in operation speed, and it is easy for SAP2000 to build an EHV transmission tower model. Additionally, SAP2000 embeds the specifications of a structural modal in most countries. As a result, SAP2000 is selected to simulate the response of an EHV tower model hit by the Chi-Chi earthquake in this study.

Based on different appearances and features, EHV towers are classified into straight suspension towers (type A), light angel suspension towers (type B), angel tension towers (type C and type D), large angel tfension towers (type E, type R, and type X), and special towers. The surface feature of different types of EHV towers varies. For example, suspension towers are usually used in a long straight line of the power grid, and tension towers are usually located at areas with big surface elevations. As mentioned earlier in the introduction, there were 3,717 345 kV EHV transmission towers until September 21, 1999, and 307 of them were damaged on that day. According to the statistics, the towers that were damaged the most were A4 towers (type A towers) and C5 towers (type C towers) [11]. Hence, this study selects an A4 EHV transmission tower to be studied and analyzed. The most damaged towers in the Chi-Chi earthquake are shown in Table I.

The details of A4 EHV transmission towers are provided by Taipower. The A4 EHV transmission tower model in SAP2000 is constructed. The model is based on the exact size, characteristics and material of a real A4 EHV transmission tower, which comprises equilateral angle steels, connection plates and bolts. Besides, the static load on the real A4 EHV transmission tower is also considered in this model. However, once the model and analysis are too complicated, the simulation might run into some problem. In order to achieve fast and accurate analysis results, the modal structure is simplified. For instance, the model does not consist of connection plates and bolts, but their weights are still considered during the simulation. The connections between the members of the model are done by fastened joints. Some junctions between the members are fixed, and therefore the hinged joints are defined as junctions. The A4 tower model uses 1406 members and 527 joints. The A4 tower in SAP2000 is shown in Fig. 2, and the detail of the A4 EHV transmission tower is shown in Fig. 3.

TABLE I
Number of the Damaged Towers in the Chi-Chi Earthquake

Type	Number of damaged towers	Type	Number of damaged towers
A	8	DH48	3
A4	15	E	3
A5	14	E5	3
C	11	E5G	4
C5	15	F	7
D	3	G	3
DH43	5	G4	5

III. Modal Analysis

The modal analysis is to simulate the structural response during vibration. By using the modal analysis, the structural response under vibration in different frequencies could be easily obtained. Also, the response caused by both interior and exterior vibration can be simulated. The simulation results can be provided to power companies for assessing the seismic hazard risk. Besides, the modal analysis is an important method for the fault diagnosis and dynamic structure design.

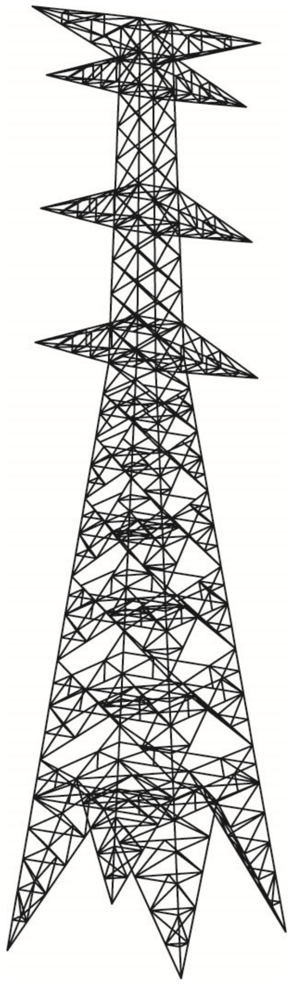
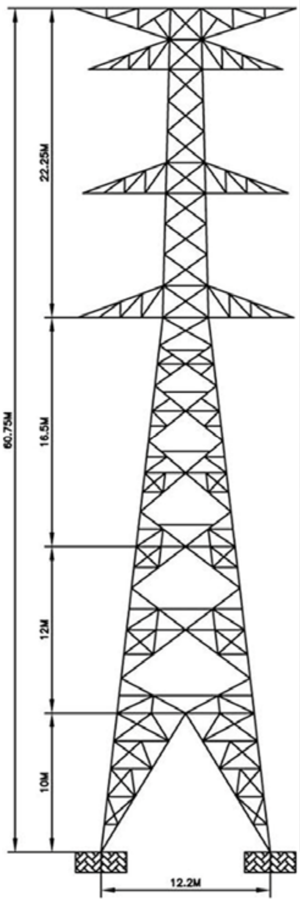


Fig. 2 The A4 tower model in SAP2000

In this study, the seismic waves in the Chi-Chi earthquake were adopted in the analysis. The data used in the simulation were collected at TCU078 station, 17:46:58, September 21, 1999. TCU station is located at Shuili Township, Nantou County, Taiwan. The Chi-Chi earthquake caused an intensity 7 seismic wave at the TCU078 station, which means the PGA was greater than 400 gal. Actually, the PGA at TCU078 then was 560.42 gal. The TCU 078 station was only 5.53 kilometers away from the epicenter.



Main post	Bracing
L100X7	L50X4, L60X5, L65X6, L90X7
L100X7	L60X5, L90X6
HL120X8	L90X7
HL120X8	L90X7
HL130X9	L90X7
HL130X9	L90X7
HL130X9	L90X6, L60X5, L50X4
HL150X10	L90X7
HL150X10	L90X7
HL175X12	L90X7
HL175X12	L90X7
HL175X12	L90X7, L60X5, L50X4
HL175X12	L80X6, L75X6
HL175X12	L60X5
HL175X15	L80X, L75X6
HL175X15	L65X6
HL175X15	L80X6, L50X4
HL175X15	L50X6 ,L50X4, L80X6
HL175X15	L80X6, L50X4 , L50X6
HL175X15	L60X5, L75X6
HL175X15	L60X5, L70X6, L80X6
HL200X15	L50X6, L60X6
HL200X15	L90X6
HL200X15	L65X6
HL200X15	L60X5, L80X6, L90X7
HL200X15	L60X5, L65X6
HL200X15	L100X7
HL200X15	L100X7, L75X6, L65X6, L90X6
HL200X15	L90X7 , L90X6
HL200X15	L90X6 , L75X6
HL200X15	L70X6, L65X6
HL200X15	L90X6
HL200X15	L50X6

Fig. 3 The structure of the A4 EHV transmission tower

The dynamic responses are influenced by some parameters, such as static load, external force and internal conditions. Additionally, the characteristics of A4 tower model itself, such as materials, if they are oversimplified in constructing the model and structural damping, would probably affect the response of the constructed model. To efficiently analyze the simulation results, the results are presented in the frequency domain rather than the time domain. It would be clearer if the damage level caused by seismic waves is identified in the frequency domain. Thus, the data after the simulation were transferred from the time domain to the frequency domain via the Fourier transform in SAP2000, and the response of the A4 EHV transmission tower model was represented by the response spectrum. The response spectrum was mapped by inputting the data to a transfer equation. According to the document provided by the Computers and Structures, Inc., the equations that transfer the data into the frequency are shown as [12]:

$$\begin{aligned}\ddot{u}(\bar{t}) = {} & \xi^2\omega^2 e^{-\xi\omega\bar{t}}\left(C_1\cos\left(\omega_d\bar{t}\right)+C_2\sin\left(\omega_d\bar{t}\right)\right) \\ & -2\xi\omega\, e^{-\xi\omega\bar{t}}\left(C_1\omega_d\left(-\sin\left(\omega_d\bar{t}\right)\right)+C_2\omega_d\cos\left(\omega_d\bar{t}\right)\right) \\ & +e^{-\xi\omega\bar{t}}\left(C_1\omega_d{}^2\left(-\cos\left(\omega_d\bar{t}\right)\right)+C_2\omega_d{}^2\left(-\sin\left(\omega_d\bar{t}\right)\right)\right)\end{aligned} \quad (1)$$

$$\xi = \frac{c}{2\sqrt{km}} < 1 \tag{2}$$

$$s = \frac{\ddot{u}_g(t_i) - \ddot{u}_g(t_{i-1})}{t_i - t_{i-1}} \tag{3}$$

$$\omega = \sqrt{\frac{k}{m}} \tag{4}$$

$$\omega_d = \omega\sqrt{1-\xi^2} \tag{5}$$

$$\overline{t} = t - t_{i-1} \tag{6}$$

$$C_1 = u(t_{i-1}) - F \tag{7}$$

$$C_2 = \frac{\dot{u}(t_{i-1}) + \xi\omega C_1 - E}{\omega_d} \tag{8}$$

$$E = -\frac{s}{\omega^2} \tag{9}$$

$$F = \frac{1}{\omega^2}\left(\frac{2\xi}{\omega}s - \ddot{u}_g(t_{i-1})\right) \tag{10}$$

Equation (1) is the Fourier transform equation that transfers the raw data into the response spectrum, where $\ddot{u}$ is the acceleration at a chosen point. u in (6) is the displacement relative to the ground, $\ddot{u}_g$ in (9) and (10) is the ground acceleration, $\bar{t}$ in (1) and (5) is the time step independent variable and s in (10) is the slope of the acceleration within a time step.

Sixty-eight points (all of them are joints and junctions between members) from the A4 EHV transmission tower model were selected to be observed and analyzed. The primary goal of the simulation in this study is to analyze the responses caused by the earthquake struck most junctions of the A4 tower model. As a result, the observed points were widely scattered on the A4 tower model. For example, the observed points were located at the bottom of the four feet, each corner and the middle of each sides of the rectangle on each layer, and the two vertexes of each arm.

IV. Results

After mapping the response spectrum sixty-eight times, it is found that the response at each junction in the same layer is the same (only for the layers below the first arm, except for the joints on the ground and the first arm itself). Therefore, in order to simplify the analysis results, repeated data are removed in this study, and the results are presented as a few specified joints. The analyzed results of each specified joints are different from others. The locations of the specified joints and the analysis results are shown in Figs. 4-9.

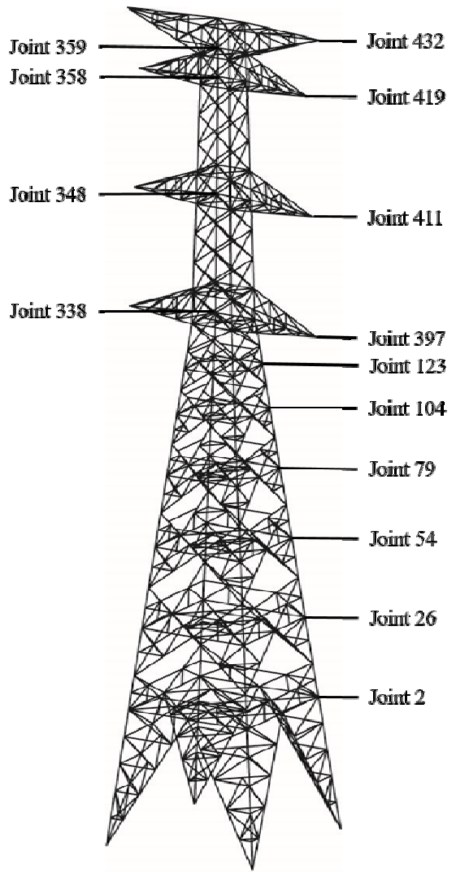


Fig. 4 Locations of the specified joints on the A4 model

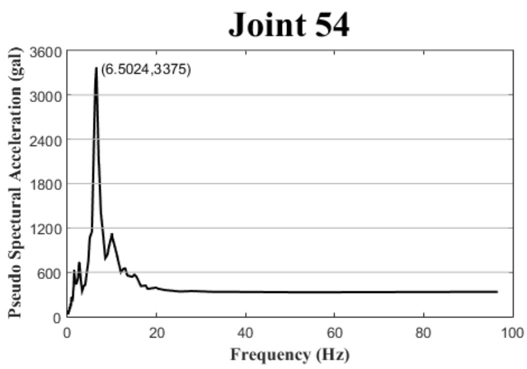


Fig. 5 The response spectrum of joint 54

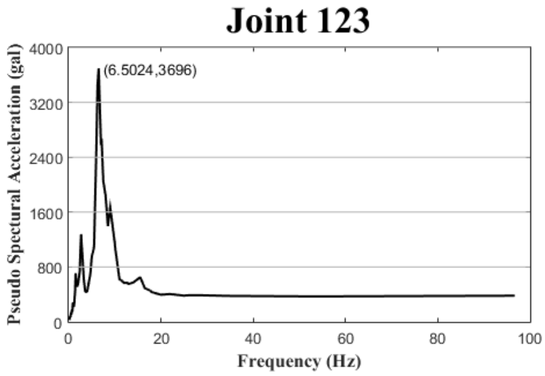


Fig. 6 The response spectrum of joint 123

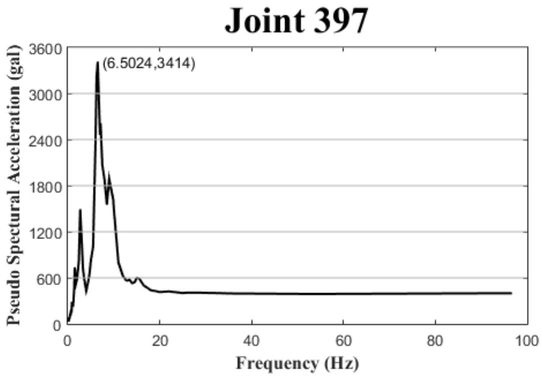


Fig. 7 The response spectrum of joint 397

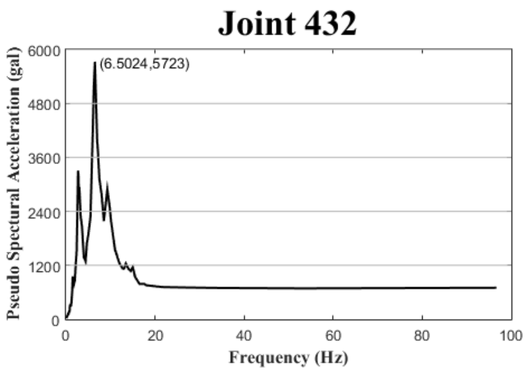


Fig. 8 The response spectrum of joint 432

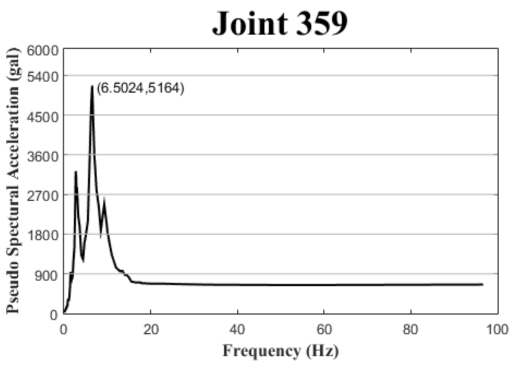


Fig. 9 The response spectrum of joint 359

The damping during the simulation was fixed at 0.02. As the figures show, the seismic waves above 20 Hz yield little acceleration and damage to the joints on the EHV tower, and the peak acceleration appears at the same frequency at most selected joints on the A4 EHV tower model. By using the statistics simulated by SAP2000, the seismic waves yield the largest acceleration at most joints when the seismic frequency is 6.5024 Hz. In addition, some joints show the second largest acceleration at other specific seismic frequencies. For instance, the wave of 2.7028 Hz yields at least half of the peak acceleration responses at joint 358, joint 359, joint 419 and joint 432, which are all located on the third arm and the top of the A4 EHV tower model. Furthermore, the seismic wave also yields a considerable acceleration at joints 2, joint 26, joint 338, joint 397 and joint 432 when the seismic frequency is between 9 Hz and 10 Hz.

Among joint 2, joint 26, joint 54, joint 79 and joint 104, the peak acceleration increases when the height of the locations of the joints increases. For joint 397, joint 419, joint 432, joint 338, joint 358 and joint 359, the trend of accelerations are also increase as the height of the locations of the joints increases. From the simulation results, it is found that the peak acceleration might occurs on the top of the whole EHV transmission tower, which means that the most serious damage might occur at the top of EHV towers during an earthquake. Though the maximum acceleration does not definitely represent the most serious damage, the top of A4 EHV towers will probably be the first joints to examine as the reference of the damage level. The results of this simulation show that this method is feasible not only for buildings but also for EHV towers The method has great potential to collaborate with related research to accurately assess the damage on EHV towers caused by earthquakes. Nevertheless, the joints located on the second arm, such as joints 348 and joint 411, respond quite differently to other parts of the A4 tower model. The response spectra of joint 348 and joint 411 are shown in Figs. 10 and 11. It is easy to find that the peak accelerations at the two joints differ from other joints. Peak accelerations occur at the wave of 2.7028 Hz, while the second largest acceleration occurs at the wave of 9.8873 Hz. Besides, the maximum acceleration during the simulation is much minor than the accelerations at other joints on other arms of the A4 EHV tower model. It is uncertain whether the queer situation brings more damage to joints or not, and it is worth observing and discussing when analyzing the damage level using the response data.

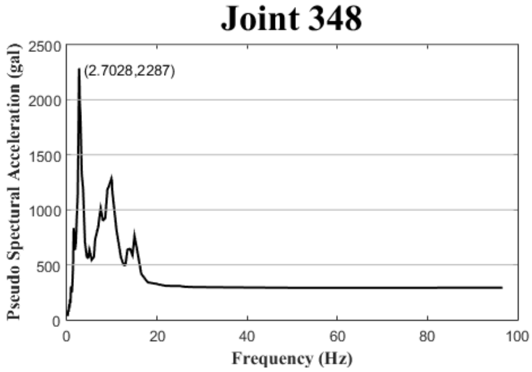


Fig. 10 The response spectrum of joint 348

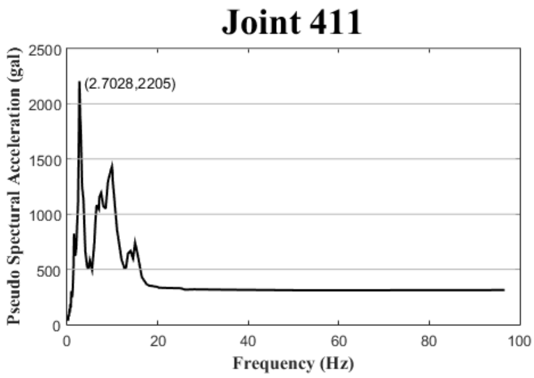


Fig. 11 The response spectrum of joint 411

V. CONCLUSION

As shown in the Section IV, it is easily identify the peak accelerations of most joints on the A4 EHV tower at the same frequency as an earthquake strikes. This outcome verifies that the methods of related researches assessing the damage level of buildings are also feasible on EHV towers. In addition to the response spectrum, the drift ratio and the fragility curve is also a significant factor for assessing the damage level of EHV towers. It is foreseeable that if the response spectrum goes with the drift ratio and fragility curves, the damage level of each joint will be instantly simulated and analyzed once an earthquake occurs. On the top of that, considering the feasibility of actually operating the proposed assessment model placed on EHV transmission towers, the future work will try to minimize monitored joints while not reducing the accuracy of the proposed model at the same time. With this model as the basis, a real time, reliable and accurate damage level assessment system can be developed, saving a large amount of money, and substantially promoting the efficiency of assessing the damage level of EHV towers.

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REFERENCES

[1] CH Loh, CY Huang, KL Wen, ML Lin, CP Hsiao, KC Chang, BJ Shih, MH Hsu, CC Lin, HK Wang, WY Chien, JF Chai, TJ Teng, CH Yeh, CS Huang, GY Liu, WH Teng, SY Chang, YK Yeh, MJ Lai, SH Wang, LL Chung, WI Liao, ZK Lee, CC Hsu. "Streamline Report of the Comprehensive Disaster Investigation on Chi-Chi Earthquake" National Center for Research on Earthquake Engineering (1999) (in Chinese)

[2] JY Hsu, CH Chen, SW Tseng, HY Ho, SW Sun, CA Wei, JS Jwo. "An Analysis of the Safety Strategy of Power System in Taiwan from the Power Outage from "729" to "921"." Research, Development and Evaluation Commission, Executive Yuan (2000) (in Chinese)

[3] GY Liu, YJ Wang, CW Liu. "Study on the Risk Analysis and Disaster Reduction Strategy of Power System" National Center for Research on Earthquake Engineering (2008)

[4] HN Li, WL Shi, GX Wang, LG Jia. "Simplified models and experimental verification for coupled transmission tower–line system to seismic excitations." Journal of Sound and Vibration 286.3 (2005): 569-585.

[5] T Yin, HF Lam, HM Chow, HP Zhu. "Dynamic reduction-based structural damage detection of transmission tower utilizing ambient vibration data." Engineering Structures 31.9 (2009).

[6] T Li, L Hongnan, L Guohuan. "Seismic response of power transmission tower-line system under multi-component multi-support excitations." Journal of earthquake and tsunami 6.04 (2012): 1250025.

[7] M. C¸elebi, A. Sanli, M. Sinclair, S. Gallant, and D. Radulescu "Real-time seismic monitoring needs of a building owner—and the solution: a cooperative effort." Earthquake Spectra 20.2 (2004): 333-346.

[8] A Kangi. "Application of Warning and Rapid Estimation of Earthquake Damage (WARED) system in unprepared cities case study: Mashhad, north east of Iran." International journal of disaster risk reduction 13 (2015): 139-144

[9] M. Erdik, K. S-es-etyan, M.B. Demircioglu, U. Hancılar, C. Zulfikar. "Rapid earthquake loss assessment after damaging earthquakes." Soil Dynamics and Earthquake Engineering 31.2 (2011): 247-266.

[10] Department of Power Supply. "Review and Summary of the Damage of Foundation of EHV Transmission Towers in Chi-Chi earthquake, 1999." Taiwan Power Company (2000) (in Chinese)

[11] LA Montejo, AL Vidot-Vega. "An Empirical Relationship between Fourier and Response Spectra Using Spectrum-Compatible Times Series." Earthquake Spectra 33.1 (2017): 179-199.

[12] Computers and Structures, Inc. "Detailed derivation of analytical equations used for response spectrum generation" (2009)